Small and Very Small Interstellar Grains

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Abstract.
This review summarizes the observational characteristics of those interstellar grains, which are prevented from entering the solar system by interactions with the heliopause. Such grains are typically less than 100 nm in radius and they reveal their presence by interstellar absorption at ultraviolet wavelengths and by non-equilibrium emissions in the red and near-infrared portions of the spectrum.

1. Introduction

The detection and mass-characterization of small solid particles, originating in interstellar space and now entering and traversing the solar system, has been a major accomplishment achieved with the current Ulysses and Galileo space probes (Gruen et al. 1994; Frisch et al. 1999). However, only the largest interstellar grains are actually detected with these experiments, because the interaction between charged grains and magnetic fields at the heliopause serves as an effective discriminator for entry into the heliosphere for grains smaller than about 100 nm radius, which is expected to lead to a significant overabundance of the excluded grains at the heliopause. This review presents the astronomical evidence for the existence of a large population of small and very small grains in the diffuse interstellar medium of the Galaxy, a population subject to exclusion at the heliopause (Frisch et al. 1999).

2. Definition of Size Domains of Interstellar Grains

Various interactions in interstellar space involving grains and grains, grains and gas, and grains and photons and other energetic particles, e.g. coagulation, shattering, accretion, sputtering, and photodestruction, in addition to the influx of newly formed grains from stellar mass outflows, assure the existence of a wide, very likely continuous, distribution of sizes of solid particles, generally referred to as interstellar grains. Recent determinations of this size distribution can be found in the work of Kim et al. (1994) and of Zubko et al. (1999). For operational reasons it makes sense to divide this distribution into three separate domains:

1. "typical" interstellar grains
2. "small" interstellar grains (SG)

3. "very small" interstellar grains (VSG)

The approximate boundaries in radius (assuming spherical grains) and mass separating these domains as well as the relative abundance of the respective grains are delineated in Table 1.

Table 1. Size Domains of Interstellar Grains.

Domain	Radius (nm)	Mass (g)	Relative Abundance
typical	100 - 1000	10^{-14} - 10^{-11}	1
small (SG)	5 - 100	10^{-19} - 10^{-14}	$\sim 10^3$
very small (VSG)	0.3 - 5	10^{-21} - 10^{-19}	$\sim 10^6$

Since "typical" interstellar grains will not be dealt with in detail in subsequent parts of this review, a brief summary of their observational characteristics is given now. "Typical" grains penetrate the heliopause and are recognizable by dust detectors on spacecraft by virtue of their heliocentric velocity vector; they are the principal contributors to extinction of star light in interstellar space at visible wavelengths, with an approximate λ^{-1} wavelength dependence; they are responsible for scattering of starlight in the interstellar medium and in reflection nebulae; their efficient alignment by interstellar magnetic fields, giving rise to interstellar polarization of star light, is testimony to their non-sperical shapes; their average temperature of 17$\pm$2 K derived from absorption of the typical interstellar radiation field, characterizes the far-infrared emission component in the electromagnetic spectrum of the Milky Way galaxy as well as other dust galaxies; and finally, despite their relatively small number density, the typical interstellar grains make up the bulk of the mass found in solid particles in the diffuse interstellar medium. A good summary of our current knowledge of typical interstellar grains can be found in the monograph by Whittet (1992).

3. Observational Characteristics of Small and Very Small Interstellar Grains

3.1. Extinction

The extinction characteristics of SGs and VSGs can be derived from Mie theory (e.g. Bohren & Huffman 1983) in the limit where the size parameter

$$x = \frac{2\pi a}{\lambda} \quad << 1 \tag{1}$$

where a is the particle radius. One finds, in this case, that the absorption efficiency Q_{abs} is directly proportional to x and the scattering efficiency, Q_{sca}, is negligibly small. As a result, the extinction is determined entirely by the absorption cross section

$$C_{abs} = 2\pi a^2 Q_{abs} \tag{2}$$

and, hence, is proportional to the volume (or mass) of the SGs and VSGs and inversely proportional to the wavelength. Consequently, at the shorter ultraviolet wavelengths, where the extinction by the larger "typical" grains has reached saturation, the presence of SGs and VSGs reveals itself through a continued wavelength-dependent extinction increasing as $1/\lambda$ with decreasing wavelength. This is indeed a general characteristic of the observed interstellar extinction, leading SGs and VSGs to absorb about 35% to 40% of the energy in the diffuse interstellar radiation field in the Galaxy. Unfortunately, in the limit set by Eqn. (1), the UV extinction curve is not particularly sensitive to the sizes of SGs or VSGs, but the extinction in the UV is a good measure of the total mass fraction of SGs and VSGs. As a consequence, competing models for interstellar grains fit the extinction observations equally well, assuming either a bi-modal size distribution (e.g. Greenberg et al. 1973) or a continuous power-law distribution (e.g. Mathis et al. 1977).

The exploration of UV extinction along numerous lines of sight with the International Ultraviolet Explorer (IUE) has revealed that the UV extinction in about 50% of all cases deviates significantly from the Galactic average, indicating that the relative mass fraction contained in SGs and VSGs relative to "typical" grains varies considerably from one line of sight to another (Fitzpatrick 1999). Possible processes which might account for these variations are accretion of SGs onto "typical" grains, which would lead to a flat extinction in the UV, selective destruction of SGs, leading to the same result, or the shattering of large grains into SGs and VSGs, producing a steep rise in UV extinction. A remarkable study by Boulanger et al. (1994) of 8 stars in the Chamaeleon cloud complex has shown that extreme cases of extinction curves can occur simultaneously within a relatively small volume of space, a testimony to the efficiency of the processes altering the size distribution of grains in space.

3.2. Scattering in the UV

Interstellar grains are highly efficient scatterers in the visible as well as the UV. The scattering characteristics of grains can be described in terms of the wavelength-dependent values of the albedo and the phase function asymmetry g, defined as the average cosine of the scattering angle. Grains comparable in size to the wavelength scatter strongly in the forward direction, resulting in g-values in excess of 0.5. Studies of the phase function asymmetry in the UV have shown that g-values are increasing with decreasing wavelength (Witt et al. 1992; Calzetti et al. 1995), consistent with a case where only large particles are scattering. As pure absorbers, SGs and VSGs affect the derived scattering properties only in that they reduce the effective dust albedo in wavelength regions where enhanced absorption by these grains occurs. Calzetti et al. (1995) demonstrated conclusively that the strong 2175 Å feature in the UV is due to pure absorption, most likely due to VSGs, and the steep rise in the far-UV extinction shortward of 1300 Å is equally associated with a decreasing albedo and hence is evidence for strong VSG absorption (Witt et al. 1993). Also, the far-UV albedo derived from observations of scattering in the diffuse interstellar dust at high galactic latitudes, which is characterized by generally steeper far-UV extinction with decreasing wavelength, was found to be 50% lower than the UV-albedo of dust in reflection nebulae, where dust particles on average are larger and the far-UV extinction is less steep (Witt et al.1997). The fact that scattering properties do not only depend on grain size but also the optical properties of the grain materials prevents us from deriving more specific information on the actual grain size distribution from scattering and extinction observations alone.

3.3. Non-Equilibrium Emission

It is likely that the lower size limit in the VSG population is set by interactions of VSGs with single photons in the interstellar radiation field. Given the density of this radiation field and the absorption cross sections of VSGs, a typical timescale between successive absorptions of energetic photons is about one day. It was recognized by Greenberg (1968), Duley (1973), and Purcell (1976) that absorptions of energetic photons by systems whose entire heat capacity is comparable to the energy of single photons will lead to large temperature fluctuations. A typical maximum temperature of a particle consisting of N atoms, absorbing a 10eV photon while at zero temperature, can be estimated as

$$T_{max} \sim \frac{10\ eV}{3Nk} \sim \frac{39000}{N}[K] \sim \frac{1}{a^3}. \tag{3}$$

Thus, depending on the vaporization temperature of the material, VSGs with less than 40 to 50 atoms will not be stable against the absorption of single UV photons (Guhathakurta and Draine), and particles slightly larger will undergo temperature excursions of 1000 K or more, resulting in temporary near- and mid-IR emission, generally referred to as non-equilibrium thermal emission (NETE). This is to be contrasted with the equilibrium thermal emission from the larger "typical" interstellar grains, which aquire a constant (low) temperature in interstellar space. First observational evidence for the presence of NETE in dusty astronomical sources was provided by Andriesse (1978) and Sellgren (1984), closely followed by the discovery by the Infrared Astronomy Satellite (IRAS) of the so-called infrared cirrus at 12 and 25 microns (Boulanger et al. 1985), which was attributed to the same NETE process. Compared to earlier model predictions, which included only "typical" grains and SGs, thus terminating the size distribution at a = 5 nm, IRAS detected diffuse galactic background radiation five orders of magnitude more intense at 25 micron, and background radiation twelve orders of magnitude more intense at 12 micron wavelength (Puget & Leger 1989). From the analysis of data on the diffuse galactic infrared background radiation we know that VSGs absorb up to 40% of the energy absorbed by dust in the Galaxy, but this ratio is highly dependent on the local environment and can vary by close to an order of magnitude for different clouds exposed to very similar radiation fields (Boulanger et al. 1988). This suggests the relative abundance of VSG is highly variable in interstellar space. The fact that such variations appear totally uncorrelated with corresponding shape parameters for the UV extinction curves seen in the same directions suggests that the combined mass fraction of SGs and VSGs does not change but that the relative distribution between VSGs and SGs does. Efficient conglomeration of VSGs can remove them from the NETE regime without affecting the total mass in small grains and, consequently, the UV extinction.With the maximum temperature of VSGs being extremely sensitive to their size (Eqn. 3), the NETE process gives particularly clear information on VSGs near the lower limit of their size distribution and their relative abundance (Draine & Anderson 1985; Weiland et al. 1986).

3.4. Photoluminescence by Interstellar Grains

A second non-equilibrium emission process associated with interstellar grains is the so-called extended red emission (ERE). This process involves the absorption of UV/visible photons, followed by photoluminescence in a broad, featureless band, beginning at a wavelength of about 540 nm with a peak of maximum emission occurring at wavelengths ranging from 610 nm to 820 nm, depending on the environment where the ERE is produced. The ERE has been observed in a wide variety of sources, ranging from reflection nebulae, planetary nebulae, and HII regions, to dusty galaxies. Most important has been the recent detection of ERE in the diffuse interstellar medium of the Milky Way galaxy over a wide range of galactic latitudes by Gordon et al. (1998), for several reasons. First, it established the ERE phenomenon as a general characteristic of Galactic dust, not just a peculiar feature seen in special environments. Second, it allowed one to determine correlations between ERE intensities and atomic hydrogen column densities, which could then be converted to correlations to dust column densities. Thus, it was possible to determine a lower limit to the ERE quantum efficiency of $(10\pm3)\%$, assuming that all photons absorbed by interstellar grains in the $90-550$ nm wavelength range are absorbed by the ERE-causing particles. This result implies that the true ERE quantum efficiency is likely substantially larger than 10%, because most absorption by interstellar grains is probably not caused by the luminescent variety. Also, the fact that 10% of all absorbed photons are contributing to the generation of the ERE implies that the ERE is produced by a fairly common grain component, derived from relatively abundant chemical elements. Examination of photoluminescence phenomena in nature in general reveals that high efficiency luminescence occurs in only such systems where the exited electron is spatially confined and other modes of recombination are effectively foreclosed. Examples are organic hydrocarbon molecules, dye molecules, or semiconductor nanoparticles. Witt et al. (1998) and Ledoux et al. (1998) have advanced proposals that ERE is produced by a population of silicon nanoparticles with about 3 nm diameter, while Seahra & Duley (1999) have published a theoretical model attributing the ERE to photoluminescence by small carbon clusters. Earlier, d'Hendecourt et al. (1986) had suggested that polycyclic aromatic hydrocarbons might be the source of the ERE, but experimental data do not at present support such a proposal. In any event, if one adopts a likely intrinsic quantum efficiency of 50%, as has been measured in semiconductor nanoparticles and large molecular systems, the Gordon et al. (1998) result implies that about 20% of the UV/optical photons absorbed in interstellar space are absorbed by luminescing VSGs.

4. Summary

The following main points have been reviewed:

1. Interstellar grains exist through a mass range of about 10^{-21} to 10^{-11} g. The lower limit of this range is determined by the stability of the particles

against photodestruction resulting from the absorption of single energetic photons. Only particles with mass in excess of 10^{-14} g are able to penetrate the heliopause.

2. Grains with radii larger than 100 nm contain most of the mass, grains smaller tham 100 nm contain most of the surface of interstellar particles.

3. UV extinction of star light provides evidence for the existence of small grains (SGs and VSGs), but is insensitive to the size distribution of small grains.

4. The ratio of the mass of small grains (SGs and VSGs) to that of larger grains is highly variable in space, even within single cloud complexes.

5. Data on scattering of star light confirm the absorption role of small grains in the diffuse interstellar medium and dense nebulae.

6. Temperature fluctuations resulting from stochastic heating of very small grains and the resulting non-equilibrium thermal emission is currently the strongest direct evidence for a large population of nm-sized particles in the interstellar medium.

7. Large variations in relative abundances of these nanoparticles occur without corresponding variations in the wavelength dependence of the far-UV interstellar extinction, suggesting that nanoparticles mainly conglomerate with other nanoparticles.

8. Photoluminescence (ERE) by grains in the diffuse interstellar medium strongly suggests the presence of photo-luminescence-efficient nanoparticles or macro-molecules which absorb about 20% of the UV/visible photons in the interstellar radiation field.

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